6. POTENTIAL FOR HUMAN EXPOSURE

6.1 OVERVIEW

Selenium has been identified in at least 494 of the 1,585 hazardous waste sites that have been proposed for inclusion on the EPA National Priorities List (NPL) (HazDat 2001). However, the number of sites evaluated for selenium is not known. The frequency of these sites can be seen in Figure 6-1. Of these sites, 490 are located within the United States and 4 are located in the Commonwealth of Puerto Rico (not shown).

Selenium is ubiquitous in the environment, being released from both natural and anthropogenic sources. The principal releases of selenium into the environment as a consequence of human activities result from the combustion of coal. Workers in the metals industry and health services, mechanics, and painters may be exposed to higher levels of selenium than the general population or persons employed in other trades. For the general population, the primary exposure pathways, in order of decreasing relative proportions, are food, water, and air. The relative proportions of these exposure pathways at hazardous waste sites is not known. Although selenium has been reported at hazardous waste sites, analysis on specific forms has not been performed. In air, selenium dioxide, methyl selenide, and dimethyl selenide are the most prevalent forms found in the atmosphere. Selenates and selenites are water soluble and, thus, can be found in water sources. Salts of selenic and selenious acids are most likely to be found in surface water and water contained in soil. Selenium sulfides would not be expected to be found at most hazardous waste sites, since they are usually manufactured for use in shampoos. Natural sources of selenium include the weathering of selenium-containing rocks to soils and volcanic eruptions.

The primary factor determining the fate of selenium in the environment is its oxidation state. Selenium is stable in four valence states (-2, 0, +4, and +6) and forms chemical compounds similar to those of sulfur. The heavy metal selenides (-2) are insoluble in water, as is elemental selenium. The inorganic alkali selenites (+4) and selenates (+6) are soluble in water (Weast 1988) and are therefore more bioavailable.

Conditions such as pH (negative log hydrogen ion concentration), Eh (oxidation-reduction potential), and the presence of metal oxides affect the partitioning of the various compounds of selenium in the environment. In general, elemental selenium is stable in soils and is found at low levels in water because of its ability to coprecipitate with sediments. The soluble selenates are readily taken up by plants and converted to organic compounds such as selenomethionine, selenocysteine, dimethyl selenide, and

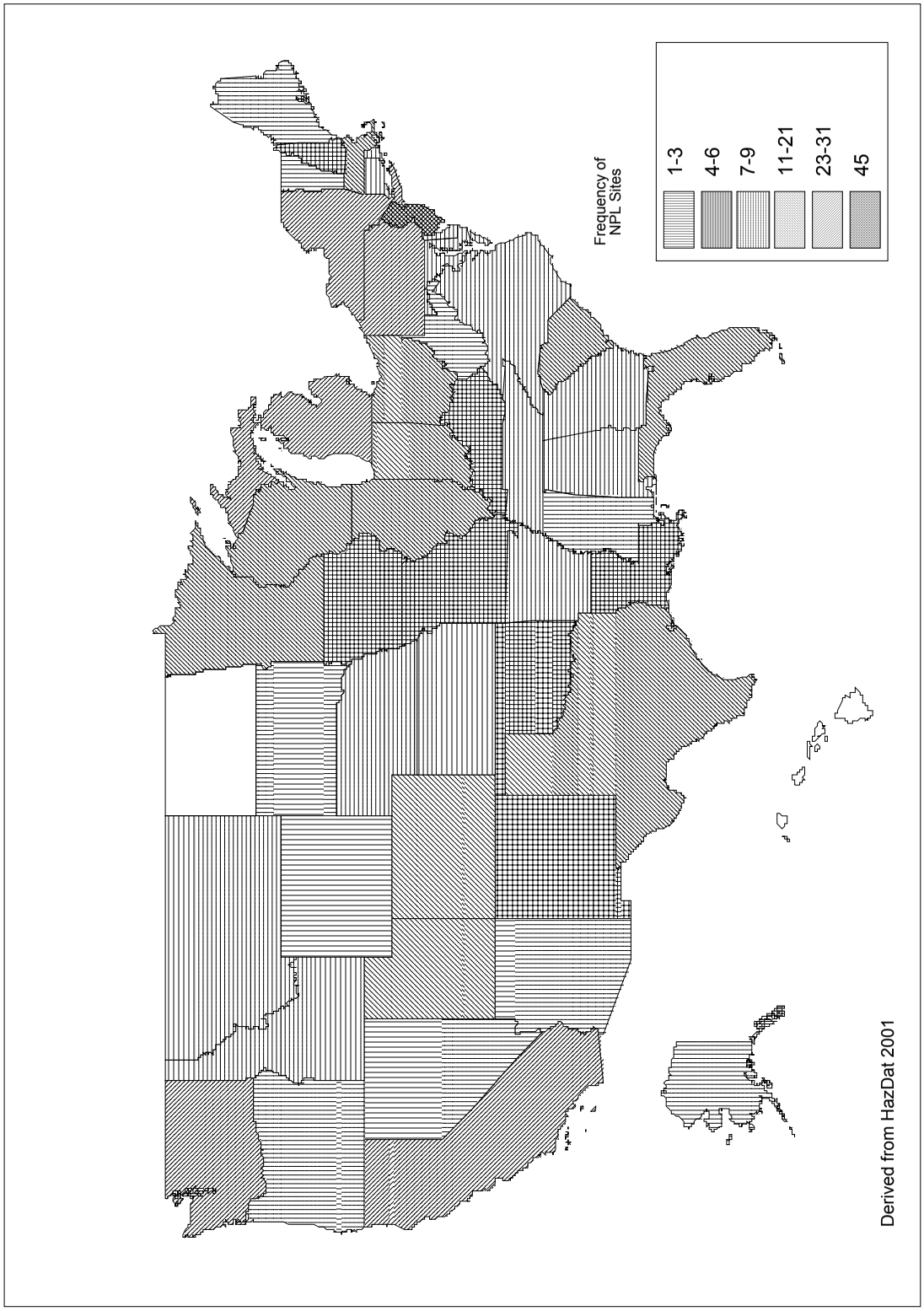

Figure 6-1. Frequency of NPL Sites with Selenium Contamination

dimethyl diselenide. Selenium is bioaccumulated by aquatic organisms and may also biomagnify in aquatic organisms.

6.2 RELEASES TO THE ENVIRONMENT

The greatest proportion of selenium released to the environment as a consequence of human activities is in coal fly ash, resulting from coal combustion. Manmade emission sources of atmospheric selenium include coal and oil combustion facilities, selenium refining factories, base metal smelting and refining factories, mining and milling operations, and end-product manufacturers (e.g., some semiconductor manufacturers). Natural atmospheric releases of selenium result from volatilization of selenium by plants and bacteria and from volcanic activity. Some selenium is released to water via sewage effluent, agricultural runoff, and industrial waste water. Selenium is released to soil primarily by leaching and weathering of the parent bedrock material, although dry and wet deposition also contribute to soil selenium levels.

According to the Superfund Amendments and Reauthorization Act (SARA), Section 313, Toxic Release Inventory (TRI99 2001), an estimated total of 338,004 pounds of selenium metal was released to air, water, land, or injected underground from manufacturing and processing facilities in the United States in 1999 (see Table 6-1). In addition, 6,622,466 pounds of selenium compounds were released to air, water, land, or injected underground in 1999 (see Table 6-2). These data include all facilities that manufacture, import, and process selenium and selenium compounds as well as facilities (electric generating facilities, petroleum facilities, etc.) with unintentional releases to the environment. The TRI data should be used with caution because only certain types of facilities are required to report. This is not an exhaustive list.

6.2.1 Air

Combustion of coal and other fossil fuels is the primary source of airborne selenium compounds. In air, elemental selenium burns to form selenium dioxide; however, during the combustion of fossil fuels, essentially all of the selenium dioxide produced should be reduced to elemental selenium by the sulfur dioxide that results from the combustion of these materials (NAS 1976a). Estimates of the quantity of selenium released to the air from fossil fuel combustion vary. Estimated annual selenium air emissions from stationary sources in the United States for 1969–1971, 1978, and 1983 were 900, 1,240, and 1,560 tons selenium/year, respectively (EPA 1974; Lee and Duffield 1979). Dulka and Risby (1976) estimated yearly releases of selenium to the air from fossil fuel combustion to be 1,000 tons. Harr (1978)

Table 6-1. Releases to the Environment from Facilities that Produce, Process, or Use Selenium

		Reported amounts released in pounds per year[a]						
State[b]	Number of facilities	Air[c]	Water	Underground injection	Land	Total on-site release[d]	Total off-site release[e]	Total on and off-site release
CA	2	5	0	No data	29,636	29,641	5	29,646
IL	3	27	No data	No data	No data	27	5,730	5,757
IN	3	0	No data	No data	2,655	2,655	2,445	5,100
LA	1	No data	No data	No data	No data	No data	No data	No data
MI	1	5	No data	No data	No data	5	10	15
NC	1	No data	No data	No data	No data	No data	No data	No data
NY	1	No data	No data	No data	No data	No data	47	47
OH	3	No data	No data	No data	No data	No data	No data	No data
OK	1	No data	285	No data	5	290	No data	290
OR	2	0	No data	No data	118,668	118,668	No data	118,668
PA	4	69,730	No data	No data	453	70,183	5,018	75,201
SC	1	35	No data	No data	116,500	116,535	No data	116,535
UT	1	No data	No data	No data	No data	No data	No data	No data
WY	1	No data	No data	No data	No data	No data	0	0
Total	26	69,802	285	0	267,917	338,004	13,255	351,259

Source: TRI99 2001

[a]Data in TRI are maximum amounts released by each facility.
[b]Post office state abbreviations are used.
[c]The sum of fugitive and stack releases are included in releases to air by a given facility.
[d]The sum of all releases of the chemical to air, land, water, and underground injection wells.
[e]Total amount of chemical transferred off-site, including to publicly owned treatment works (POTW).

Table 6-2. Releases to the Environment from Facilities that Produce, Process, or Use Selenium Compounds

		Reported amounts released in pounds per year[a]						
State[b]	Number of facilities	Air[c]	Water	Underground injection	Land	Total on-site release[d]	Total off-site release[e]	Total on and off-site release
AL	3	4,405	3,800	No data	43,600	51,805	356	52,161
AR	1	474	No data	No data	No data	474	13,946	14,420
AZ	3	1,284	0	No data	640,900	642,184	6,795	648,979
CO	1	No data	No data	No data	No data	No data	No data	No data
FL	2	7,005	No data	No data	350	7,355	15	7,370
GA	6	45,929	461	No data	27,639	74,029	7,470	81,499
IA	5	No data	No data	No data	No data	No data	90	90
ID	1	1,830	No data	No data	97,940	99,770	10	99,780
IL	9	6,333	4,200	No data	23,553	34,086	79,458	113,544
IN	4	4,632	2,185	No data	7,596	14,413	6,012	20,425
KS	1	5	No data	No data	250	255	5	260
KY	4	16,307	5,800	No data	36,896	59,003	No data	59,003
LA	2	193	25	No data	No data	218	27,262	27,480
MA	1	245	0	No data	20	265	5,600	5,865
MD	2	16,101	1,001	No data	730	17,832	4,916	22,748
MI	5	18,306	2,733	No data	799,173	820,212	422,068	1,242,280
MN	1	50	2,300	No data	No data	2,350	90	2,440
MN	1	750	No data	No data	28,000	28,750	1,250	30,000
MO	1	No data	No data	No data	No data	No data	No data	No data
NC	5	65,019	915	No data	32,710	98,644	10	98,654

Table 6-2. Releases to the Environment from Facilities that Produce, Process, or Use Selenium Compounds (*continued*)

		Reported amounts released in pounds per year[a]						
State[b]	Number of facilities	Air[c]	Water	Underground injection	Land	Total on-site release[d]	Total off-site release[e]	Total on and off-site release
NE	4	135	51	0	1,601,025	1,601,211	0	1,601,211
NM	5	1,187	0	No data	157,003	158,190	18,005	176,195
NY	1	0	No data	No data	No data	0	15,151	15,151
OH	7	60,889	9,817	No data	65,491	136,197	35,130	171,327
OK	2	11,595	No data	No data	26,267	37,862	147	38,009
PA	9	52,484	1,596	No data	33,100	87,180	33,616	120,796
SC	1	3,393	No data	No data	8,869	12,262	No data	12,262
TN	2	13,510	5,050	No data	28,305	46,865	500	47,365
TX	13	160,337	177	33,509	287,207	481,230	3,554	484,784
UT	5	9,937	1,255	No data	1,869,154	1,880,346	3,529	1,883,875
WA	1	No data	No data	No data	No data	No data	No data	No data
WI	1	No data	No data	No data	No data	No data	No data	No data
WV	9	77,743	3,700	No data	101,983	183,426	9,265	192,691
WY	2	10,544	No data	No data	35,508	46,052	No data	46,052
Total	121	590,622	45,066	33,509	5,953,269	6,622,466	694,250	7,316,716

Source: TRI99 2001

[a]Data in TRI are maximum amounts released by each facility.
[b]Post office state abbreviations are used.
[c]The sum of fugitive and stack releases are included in releases to air by a given facility.
[d]The sum of all releases of the chemical to air, land, water, and underground injection wells.
[e]Total amount of chemical transferred off-site, including to publicly owned treatment works (POTW).

estimated that 1,500 tons were released annually, with additional air releases from industrial and municipal wastes totaling 2,700 tons and 360 tons, respectively. Selenium releases to the air are likely to increase as more coal is burned in the future. The estimated selenium emissions from Canadian non-ferrous smelters (stack plus fugitive) were 3.02 tons in 1993 (Skeaff and Dubreuil 1997).

Incineration of rubber tires, paper, and municipal waste is an additional source of atmospheric selenium. Hashimoto et al. (1970) reported selenium concentrations in rubber tires to be 1.3 mg/kg. Seventy different kinds of paper have been found to contain selenium (West 1967). Combustion of municipal solid waste results in stack emissions ranging from 0.00098 to 0.00216 pounds (0.44–0.98 g) of selenium per ton of refuse (Johnson 1970).

The amount of selenium contributed to the air by other sources is not known. Microbial action within the soil may also contribute selenium to the air (Fishbein 1983). Selenium biomethylation volatilizes about 3,000 tons of selenium per year into the atmosphere, which eventually returns to earth in rainfall (NAS 1976a). Volcanic gas is suspected to be the major natural source of atmospheric selenium. Certain plants metabolize inorganic selenium compounds to volatile selenium in the forms of dimethyl selenide (Lewis et al. 1971) and dimethyl diselenide (Evans et al. 1968). Animals are also capable of volatilizing selenium and releasing dimethyl selenide in expired air (Schultz and Lewis 1940).

Fly ash settling ponds (which contain high concentrations of selenium) and hazardous waste sites where selenium compounds were disposed of in the past are potential sources of atmospheric selenium through fugitive dust emissions. Selenium emissions from these potential sources have not been quantified.

According to TRI, an estimated total of at least 69,802 pounds of selenium metal and 590,622 pounds of selenium compounds were discharged to the air from manufacturing and processing facilities in the United States in 1999 (TRI99 2001) (see Tables 6-1 and 6-2). The data listed in the TRI tables should be used with caution since only certain types of facilities are required to report. This is not an exhaustive list.

Selenium has been identified in air at 13 sites collected from the 494 NPL hazardous waste sites where it was detected in some environmental media (HazDat 2001).

6.2.2 Water

Surface waters can receive selenium from the atmosphere by dry and wet deposition, from adjoining waters that may contain selenium, from surface runoff, and from subsurface drainage. Sewage treatment plants are another source of selenium releases to water. Effluents from sewage treatment plants and oil refineries appear to be the major sources of selenium in the San Francisco estuarine system (Cutter 1989). In a study of direct discharges from oil refineries in San Francisco Bay, the average selenium concentration in the effluent was 0.067 mg/L with a range of 0.0066–0.156 mg/L (Barceloux 1999; Cutter 1989). Approximately 50–76% of the total selenium in the effluents was selenite. This proportion of selenite is higher than that found in natural estuary sources in the San Francisco Bay (Cutter 1989). About 150,000–460,000 tons of selenium per year are deposited in coal fly ash (Andren and Klein 1975; Doran 1982). Selenium from fly ash settling ponds and hazardous waste sites could reach surface water via runoff or could reach groundwater via leaching. Concentrations of 0.10–0.25 mg/L in a settling basin effluent from coal fly ash in North Carolina were reported by Lemly (1985). Overflow from the ash basin of a coal fired electric generating facility to Belews Lake resulted in surface water selenium concentrations of 0.005–0.020 mg/L in the lake basin. These levels have been reduced considerably since 1986 when the discharge of selenium laden waste water to the lake was discontinued. The peak selenium concentration in 1996 was <0.001 mg/L (Lemly 1997). Selenium concentrations as high as 0.28 mg/L have been reported for raw sewage, 0.045 mg/L for primary effluent, and 0.050 mg/L for secondary effluent (Baird et al. 1972). Irrigation drainage from seleniferous soils can increase selenium concentrations in surface water and has resulted in levels that are toxic to wildfowl at Kesterson National Wildlife Refuge in California (Ohlendorf et al. 1986a, 1988).

Selenium was found to be released during coal mining because of the oxidation of selenium-bearing pyrite (Dreher and Finkelman 1992).

According to the TRI, an estimated total of 285 pounds of selenium metal and 45,066 pounds of selenium compounds were discharged to water from manufacturing and processing facilities in the United States in 1999 (TRI99 2001) (see Tables 6-1 and 6-2). The data listed in the TRI tables should be used with caution since only certain types of facilities are required to report. This is not an exhaustive list.

Selenium has been identified in groundwater at 266 sites and surface water at 102 sites collected from the 494 NPL hazardous waste sites where it was detected in some environmental media (HazDat 2001).

6.2.3 Soil

The primary factor that controls selenium concentrations in soil is the selenium content of the parent bedrock materials that release selenium via weathering processes and leaching (NAS 1976a). Natural weathering processes are thought to release about 100,000–200,000 metric tons of selenium per year (Andren and Klein 1975). Atmospheric deposition of selenium also contributes to selenium in the soil. In the past, selenium was used in pesticide products, but because of its stability in soils and subsequent contamination of food crops, its use in pesticide products is now restricted. The release of selenium to soil from fly ash settling ponds and hazardous waste sites has not been quantified.

According to the TRI, an estimated total of 267,917 pounds of selenium metal and 5,953,269 pounds of selenium compounds were discharged to land from manufacturing and processing facilities in the United States in 1999 (TRI99 2001). In addition, 33,509 pounds of selenium compounds were injected underground (see Table 6-2). The data listed in the TRI tables should be used with caution since only certain types of facilities are required to report. This is not an exhaustive list.

Selenium has been identified in soil at 182 sites and sediment at 108 sites collected from the 494 NPL hazardous waste sites where it was detected in some environmental media (HazDat 2001).

6.3 ENVIRONMENTAL FATE

The behavior of selenium in the environment is influenced to a large degree by its oxidation state and the consequent differences in the behavior of its different chemical compounds (Callahan et al. 1979c; NAS 1976a). The oxidation state of selenium in the environment is dependent on ambient conditions, particularly on pH, pE, and biological activity (Maier et al. 1988).

6.3.1 Transport and Partitioning

The volatile selenium compounds that partition into the atmosphere include the inorganic compounds selenium dioxide and hydrogen selenide and the organic compounds dimethyl selenide and dimethyl diselenide. Hydrogen selenide is highly reactive in air and is rapidly oxidized to elemental selenium and water (NAS 1976a), but the other compounds can persist in air.

Selenium compounds released to the atmosphere can be removed from it by dry or wet deposition to soils or to surface water. The annual wet deposition rate of selenium at two rural/agricultural sites in Queenstown, Maryland and St. Mary's, Maryland were 287 and 140 μg/m^2-year, respectively (Scudlark et al. 1994). Selenium concentrations ranging from 0.04 to 1.4 μg/L have been detected in rain and snow (Hashimoto and Winchester 1967). Kubota and coworkers (1975) reported selenium concentrations of 0.02–0.37 μg/L in rainwater at several locations in the United States and Denmark. Selenium was detected at average concentrations of 5.60–7.86 μg/L during four rainfall events in Riyadh, Saudi Arabia (Alabdula'aly and Khan 2000).

The forms of selenium expected to be found in surface water and the water contained in soils are the salts of selenic and selenious acids. Selenic acid (H_2SeO_4) is a strong acid. The soluble selenate salts of this acid are expected to occur in alkaline waters. Sodium selenate is one of the most mobile selenium compounds in the environment because of its high solubility and inability to adsorb onto soil particles (NAS 1976a). Selenious acid (H_2SeO_3) is a weak acid, and the diselenite ion predominates in waters between pH 3.5 and 9. Most selenites are less soluble in water than the corresponding selenates (NAS 1980b).

Selenium in an aquatic environment is bioaccumulated by aquatic organisms (Chau and Riley 1965; Ohlendorf et al. 1986a; Rudd and Turner 1983a; Saiki and Lowe 1987). Lemly (1985) has reported bioconcentration factors (BCFs) of 150–1,850 and bioaccumulation factors (BAFs) of 1,746–3,975 for selenium in freshwater. In the Kesterson National Wildlife Refuge in the San Joaquin Valley of California, elevated levels of selenium have been measured (dry weight) in algae (average 35 mg/kg), midge larvae (139 mg/kg), dragonfly and damselfly nymphs (average 122 and 175 mg/kg, respectively), and mosquito fish (170 mg/kg) (Ohlendorf et al. 1986b). For comparison, the mean concentrations of selenium found in fish throughout the United States in the 1976–1977, 1978–1979, and 1980–1981 National Pesticide Monitoring Program were 0.56, 0.46, and 0.47 mg/kg wet weight, respectively (Lowe et al. 1985; May and McKinney 1981; Ohlendorf et al. 1986b). Similarly, Lemly (1985) found elevated selenium concentrations in aquatic organisms living in a power plant cooling reservoir in North Carolina. The degree of bioaccumulation of selenium exhibited a stable pattern over several years, with selenium concentrations (wet weight) as follows: fish (6–35 mg/kg) > benthic insects (12–15 mg/kg) > annelids (10–12 mg/kg) > molluscs and crustaceans (5–9 mg/kg) > periphyton (4–6 mg/kg) (Ohlendorf et al. 1986a). In fish, selenium was concentrated in visceral tissue (25–35 mg/kg wet weight) more than in skeletal muscle (6–11 mg/kg wet weight). Adams (1976) reported BCFs of 62.1, 14.3, 6.3, 3.2, and 10.5 for selenium in the viscera, gill, head and tail, muscle, and whole trout, respectively. The BCFs and

BAFs for selenium in visceral tissue (i.e., heart, hepatopancreas, spleen, and gonads) of fish have been estimated to range from 35 to 1,850 and from 1,058 to 3,980, respectively (Lemly 1982, 1985). Lemly (1985) also estimated BAFs for selenium in skeletal muscle of fish to range from 485 to 1,746, depending on the species. Maier et al. (1988) estimated selenium BAFs for algae to range from 100 to 2,600, and Besser et al. (1993) estimated BCFs of 16,000 for algae, 200,000 for daphnids, and 5,000 for bluegills from exposures to 1 µg/L selenomethionine. Selenite was more concentrated than selenate for algae and daphnids, whereas bluegills concentrated both inorganic species about equally (Besser et al. 1993). Selenium accumulation from selenomethionine occurred more readily than from selenite or selenate (Besser et al. 1989).

Some evidence indicates that under natural conditions selenium might biomagnify in aquatic organisms (Lemly 1985; Maier et al. 1988; NCDNR 1986; Sandholm et al. 1973). Biomagnification is evidenced by progressively higher concentrations of an element or substance in organisms at successively higher trophic levels. More than 50% of the selenium contained in sediments in the ponds and the reservoir in the Kesterson National Wildlife Refuge in California occur in organic forms (Maier et al. 1988), resulting from the synthesis and bioaccumulation of organic selenium before the plants die and decay on the bottom.

In soils, pH and Eh are determining factors in the transport and partitioning of selenium. Elemental selenium is essentially insoluble and may represent a major inert "sink" for selenium introduced into the environment under anaerobic conditions (NAS 1976b). Heavy metal selenides and selenium sulfides, which are also insoluble, predominate in acidic (low pH) soils and soils with high amounts of organic matter. Selenium in this form is immobile and will remain in the soil. The selenides of other metals such as copper and cadmium are of low solubility (NAS 1976b). Sodium and potassium selenites dominate in neutral, well-drained mineral soils, where some soluble metal selenites may be found as well. In alkaline (pH>7.5), well-oxidized soil environments, selenates are the major selenium species. Because of their high solubility and low tendency to adsorb onto soil particles, the selenates are very mobile (Kabatas-Pendias and Pendias 1984) and are readily taken up by biological systems (Klaassen et al. 1986) or leached through the soil. Gerritse et al. (1982) found selenium to be very mobile in sewage sludge leachate. They reported a K_ds (distribution coefficient = [concentration of selenium sorbed on soil or rock]/[concentration of selenium in solution]) of 14.9 mL/g for sandy loam and 5.91 mL/g for sludge-treated sandy soils. Selenite forms stable ferric oxide-selenite adsorption complexes in acid or neutral soils (Geering et al. 1968).

When environments favor the soluble forms of selenium (alkaline and oxidizing conditions), these forms can be accumulated by plants. In addition, although both selenite (Se^{4+}) and selenate (Se^{6+}) are soluble forms of selenium, selenate was found to be the preferred form of selenium taken up by plants (Banuelos and Meek 1990). Preferential uptake of selenate may be caused by its tendency to be less strongly adsorbed to soil particles and organic matter than selenite (Banuelos and Meek 1990). Selenium uptake by plants is influenced by many factors including soil type, pH, colloidal content, concentration of organic material, oxidation-reduction potentials in the root-soil environment, and total level of selenium in the soil (Fishbein 1983; Robberecht et al. 1982). In acidic soils (pH 4.5–6.5) and under high moisture conditions, selenium is in the form of selenite and is bound to colloids as iron hydroxide selenium complexes. These complexes are insoluble and generally not bioavailable to plants (Galgan and Frank 1995). In basic soils (pH 7.5–8.5), selenium is present as soluble selenate. Soluble selenates (principally sodium selenate) appear to be responsible for most of the naturally occurring accumulation of high levels of selenium by plants, although much of the total selenium in soil may be present in other forms (NAS 1976a). The use of lime and plant ash as fertilizers, which would raise the pH of the soil and favor the formation of selenate, has been implicated as a contributing factor in the accumulation of selenium in crops grown in high selenium soil found in certain regions of China (Yang et al. 1988).

6.3.2 Transformation and Degradation

6.3.2.1 Air

Selenium dioxide released to the air from the combustion of fossil fuels should be largely reduced to elemental selenium by sulfur dioxide formed during the combustion (NAS 1976b). During a 1991 study, Oehm et al. found that selenium dioxide reacting with atmospheric moisture generates selenious acid aerosols. Hydrogen selenide is unstable in air and is oxidized to elemental selenium and water (NAS 1976a). Hazards from hydrogen selenide are expected, therefore, to be confined to occupational settings where the confined gas might build up to hazardous levels despite oxidative losses (NAS 1976a). Dimethyl selenide and methyl selenide are volatile organic compounds that can partition into and persist in the atmosphere. Other selenium compounds released to the atmosphere as dust can be removed by wet deposition (in rain or snow) or by dry deposition.

6.3.2.2 Water

In general, the more soluble and mobile forms of selenium (e.g., selenite and selenate) dominate under aerobic (high oxygen concentrations) and alkaline (high pH) conditions (NAS 1976a; Shamberger 1981). Selenates have been predicted thermodynamically to predominate under aerobic conditions, but a review of the literature indicates that both selenites and selenates are equally common in surface waters (Robberecht and Van Grieken 1982). For selenites in solution, equilibria will be set up between H_2SeO_3, $HSeO_3^-$, SeO_3^-, $HSe_2O_5^-$, and $Se_2O_5^{2-}$. The relative concentrations of these species will be determined by the pH of the solution and the total concentration of the electrolytes. Between pH 3.5 and 9, dissolved selenite would be expected to be present predominantly as the diselenite ion, whereas dissolved selenate would occur predominantly as SeO_4^{2-}. Sodium predominates as the counter ion of selenate and selenite in most surface waters.

A study completed by Bender et al. (1991) using a simulated laboratory pond found that bacteria and cyanobacteria have two possible mechanisms for the uptake and transformation of selenate. The uptake mechanism involves the reduction of selenate to elemental selenium that will be physically held within the biological mat. The microorganisms were also found to cause the transformation of soluble selenium into volatile alkyl selenium compounds (Bender et al. 1991).

In some deep aquifers, selenium transport in groundwater was found to be strongly retarded (White et al. 1991). This phenomena is thought to be caused by chemical reduction and precipitation mediated by microbial activity.

Under acidic conditions, selenite can be rapidly reduced to elemental selenium by mild reducing agents such as ascorbic acid or sulfur dioxide (NAS 1980b). Selenate can be converted to selenite or elemental selenium in aquatic systems, but this reaction is slow relative to other transformations. Once formed, elemental selenium is stable over a wide range of pH values and a range of mildly oxidizing to reducing conditions. The formation of various metal selenides is favored by acidic and reducing conditions (NAS 1976b), as found in organic-rich sediments.

Aquatic organisms can convert selenium to both inert and soluble forms. Duckweed, phytoplankton, bacteria, and fungi have been demonstrated to synthesize selenoamino acids from absorbed inorganic selenium compounds (Maier et al. 1988). These selenoamino acids are not likely to be found at significant dissolved concentrations in water, however, because amino acids are rapidly catabolized by

bacteria. Benthic bacteria and fungi are capable of methylating elemental and inorganic selenium salts (Chau et al. 1976). Hydrogen selenide can be formed in a reducing environment (Cutter 1982; NAS 1976a). Both hydrogen selenide and the methylated forms of selenium are unstable in water and would be expected to rapidly volatilize to the atmosphere (Fishbein 1983).

6.3.2.3 Sediment and Soil

In soils, elemental selenium and inorganic selenium compounds such as sodium selenite can be methylated by microorganisms and subsequently volatilized to the atmosphere (Doran 1982; Fishbein 1983; Shamberger 1981). Microorganisms such as *Aeromonas*, *Flavobacterium*, and *Pseudomonas* are suspected of methylating inorganic and organic selenium compounds to dimethyl selenide and dimethyl diselenide (Doran and Alexander 1976; Fishbein 1983; Reamer and Zoller 1980). Microbes cultured from rhizosphere of bulrush (*Scirpus robustus*) plants were shown to biomethylate soluble selenate and selenite and substantially volatilize these compounds over a 15-day incubation period (Azaizeh et al. 1997). Temperature plays a significant role in the microorganism-mediated volatilization of selenium compounds; temperature reduction from 20 to 10E C resulted in a 25% reduction, and from 20 to 4 EC resulted in a 90% reduction in the dimethyl selenide produced (Chau et al. 1976). Reamer and Zoller (1980) examined microbial transformation of selenium in aerobic sewage contaminated with elemental selenium and selenite. They found dimethyl selenide to be the principal microbial product at low selenite concentrations (1–10 mg/kg), whereas dimethyl diselenide and dimethyl selenone were the principal products at higher selenite concentrations (100–1,000 mg/kg). Dimethyl selenide was the only product recovered from sludge contaminated with elemental selenium (Reamer and Zoller 1980). In general, microorganisms appear to methylate organic selenium compounds more readily than either selenite or selenate (Maier et al. 1988). Elemental selenium is converted to methylated selenium compounds the least rapidly (Maier et al. 1988). Selenium methylation and subsequent return from the atmosphere as selenite in rainwater is likely to be the major natural process by which selenium cycling occurs in the environment (Doran 1982).

Demethylation of the trimethylselenonium ion can also occur in soil. Microorganisms are evidently required for this reaction since it did not occur in autoclaved soil (Yamada et al. 1994). Selenium added to the soil as trimethylselenonium was not recovered in the soil, suggesting that trimethylselenonium was demethylated to gaseous selenium compounds, for example, dimethylselenide.

Terrestrial plants take up soluble selenate and selenite and biosynthesize organic selenium compounds, predominantly selenomethionine and, to a lesser extent, selenocysteine. Selenates tend to be taken up by plants from soils more readily than selenites, in part because selenites tend to adsorb more strongly to soils (Dimes et al. 1988; Zhang et al. 1988). These compounds can be released to the soils once the plants die and decay. Water-soluble organic selenium compounds are also probably readily taken up by plants (Shamberger 1981; Shrift 1964).

6.4 LEVELS MONITORED OR ESTIMATED IN THE ENVIRONMENT

Selenium can be detected in most biological and nonbiological materials in the environment. Selenium occurs in aquatic and terrestrial organisms as well as in water, air, and soil. Among foods consumed by humans, meat products generally contain the highest concentration of selenium while vegetables and fruits contain the lowest. Brazil nuts contain extremely high levels of selenium since they grow in the foothills of the Andes Mountains, where the soils are high in selenium (Secor and Lisk 1989). Cereals contain intermediate levels of selenium.

6.4.1 Air

Background ambient air concentrations of selenium are generally in the nanogram per cubic meter (ng/m^3) range (Harrison et al. 1971; John et al. 1973; Peirson et al. 1973). Dams et al. (1970) found concentrations of selenium in suspended air particulate matter of 2.5 ng/m^3 in Niles, Michigan, and 3.8 ng/m^3 in East Chicago, Indiana. During 1968–1969, 18 air samples collected around Buffalo, New York, showed a range of 3.7–9.7 ng/m^3 (Pillay et al. 1971). Based on these results, the National Academy of Sciences (NAS 1976a) has estimated that the average selenium concentration in the air is well below 10 ng/m^3. A monitoring study to determine the seasonal variation of pollutants in the air of Alaska was conducted from 1984 to 1987 (Sturges and Shaw 1994). The average concentration of selenium in Poker Flats, Alaska was 0.035 ng/m^3 (June 1 through January 31, 1984–1987) and 0.067 ng/m^3 (February 1 through May 31, 1984–1987). The nearly 2-fold increase in concentration during the spring months were attributed to local marine biogenic volatilization of selenium, and not a coal burning origin (Sturges and Shaw 1994). Selenium was detected in the ambient atmosphere at seven sites in the United Kingdom at concentrations ranging from 0.1 to 42.3 ng/m^3 (Lee et al. 1994). The lowest levels were observed in the rural areas of Chilton and Windermere with mean concentrations of 1.3 and 0.9 ng/m^3, respectively. The highest mean concentration of 16.7 ng/m^3 was observed in the industrial area of Walsall.

6.4.2 Water

Selenium has been detected in surface waters and groundwaters in the United States at generally low concentrations. Selenium has been detected in oceans at an average value of $9x10^{-5}$ mg/L (0.09 µg selenium/L) (Schutz and Turekiam 1965). In a study of selenium concentrations in major watersheds of the United States, selenium was detected in only 2 of 535 samples (<0.5%) at a concentration greater than the lowest detection limit of 0.010 mg/L (Lakin and Davidson 1967). Examination of the EPA STORET database for the state of North Carolina revealed that only 3.3% of 657 samples of surface water contained more than 0.001 mg/L, and the highest value was 0.012 mg/L (NCDNR 1986). Watersheds that receive selenium contaminated waste water have high levels of selenium in surface water samples. The selenium concentration in Lake Belews, North Carolina has dropped from a maximum value of about 0.020 mg/L (pre-1986) to <0.001 mg/L in 1996, due to the discontinued release of selenium laden waste water from a local coal fired power plant (Lemly 1997). The selenium concentration in portions of Pigeon River and Pigeon Lake, Michigan that receive waste water input from a coal fly ash disposal facility were <0.001–0.0075 mg/L (Besser et al. 1996).

High selenium levels are more likely to be found in irrigation return waters, seeps, springs, and shallow wells where seleniferous soils may contribute to the selenium content of the water. Glover et al. (1979) found that under unusual geological conditions, selenium concentrations in groundwater may reach 0.60 mg/L. In another study conducted in a seleniferous area of South Dakota, 34 of 44 wells did not show any measurable selenium; however, the remaining 10 had concentrations ranging from 0.050 to 0.339 mg/L (Smith and Westfall 1937). Selenium concentrations determined in 107 irrigation and 44 livestock well waters in the San Joaquin area of California exceeded 0.010 mg/L in 26 wells, but exceeded 0.020 mg/L in only 11 wells (Oster et al. 1988a). The maximum concentration was 0.272 mg/L (Oster et al. 1988a).

Selenium accumulation in agricultural drainage waters and basins has been documented in the western United States, particularly in California. The problem was first discovered in the Kesterson Wildlife Refuge in the San Joaquin Valley of California. In 1975, the U.S. Bureau of Reclamation finished construction of an 85-mile subsurface agricultural water drain that terminated in a series of evaporation ponds called Kesterson Reservoir. By 1983, however, it was confirmed that the drain waters contained high concentrations of selenium (>1.35 mg/L in some areas) leached from the soil by application of irrigation water (Maier et al. 1988). Because the high selenium levels produced death and deformities in fish and waterfowl, delivery of subsurface water to Kesterson was terminated in 1986 (Lewis 1988).

Measurements of trace elements in the 27 other evaporation basins in the San Joaquin Valley have revealed only 3 basins with total selenium exceeding 0.10 mg/L and only 50 acres of evaporation basin cells with selenium concentrations in excess of 1.0 mg/L (CRWQCB 1988).

6.4.3 Sediment and Soil

Selenium is estimated to be the 69th most abundant element in the earth's crust, with an average concentration of 0.05–0.09 mg/kg (Glover et al. 1979). Chemically, selenium closely resembles sulfur. Consequently, sulfides of bismuth, iron, mercury, silver, copper, lead, and zinc have been found to contain selenium (Shamberger 1981). Selenium is concentrated in the sulfide minerals galena, chalcopyrite, arsenopyrite, sphalerite, pyrite, marcasite, and pyrrhotite (Coleman and Delevaux 1957). Jarosite and barite have also been found to contain selenium at low levels. The sulfides containing the highest selenium concentrations are those associated with uranium ores in sandstone-type deposits in the western United States. In the immediate vicinity of sandstone-type uranium deposits, selenium concentrations as high as 1,000 mg/kg have been found (Shamberger 1981). Hydrothermal ore is also known to contain high concentrations of selenium. The best known are epithermal gold, silver, antimony, and mercury deposits (Shamberger 1981). Selenium has been found in volcanic rocks in the western United States at concentrations as high as 120 mg/kg (Glover et al. 1979).

Various studies estimated selenium concentration of most soils to be between 0.01 and 0.2 mg/kg (Sindeeva 1964). One study analyzed several thousand soil samples in the United States and found that most seleniferous soils contained <2 mg/kg, with a maximum concentration of <100 mg/kg (Rosenfeld and Beath 1964). The highest U.S. soil levels of selenium are found in areas of the West and Midwest.

Atmospheric deposition of selenium from mining and smelting activities also appears to be a source to soils and plants (Glooschenko and Arafa 1988). In this study, an indirect relationship between distance from smelters and selenium concentration was shown using *Sphagnum fuscum* as an indicator. Washout of atmospheric selenium by precipitation appeared to be the primary mechanism for accumulating selenium in soils and plants in the vicinity of smelters (Glooschenko and Arafa 1988).

Sandstone has been found to contain selenium in varying concentrations, but most probably contains <1 mg/kg (Rosenfeld and Beath 1964). However, sandstone in Wyoming has been found to contain >100 mg/kg (Beath et al. 1946). Generally, the selenium concentration of limestone is low; however,

shales of the Niobrara formation in South Dakota have been found to contain over 40 mg/kg. The range of selenium concentrations in phosphate rocks is <1–300 mg/kg (NAS 1976a).

The shales appear to contain consistently higher concentrations of selenium than limestone or sandstone. Despite the fact that the shales vary so widely in their selenium concentration, they are fairly reliable indicators of soils high in selenium (NAS 1976a).

The disposal of selenium contaminated waste water has resulted in elevated selenium levels in sediments of Lake Belews, North Carolina. The concentration of selenium in sediments ranged from 4 to 12 µg/g (pre-1986), but has dropped to 1–4 µg/g (1996) due to the discontinued release of selenium laden waste water from a local coal fired power plant (Lemly 1997). Selenium was measured in 445 surface soil samples from Florida with a concentration range of 0.01–4.62 µg/g and an arithmetic mean of 0.25 µg/g (Chen et al. 1999). Selenium was detected in soils and bed sediment from the South Platter River Basin at concentrations of 0.30–3.80 µg/g (Heiny and Tate 1997). The highest levels were observed in areas consisting of a high degree of Precambrian rock formation.

6.4.4 Other Environmental Media

Coal and Oil. Petroleum has been found to contain 500–950 mg/kg crude petroleum and 500–1,650 mg/kg heavy petroleum (Hashimoto et al. 1970). An average of 2.8 mg/kg coal has been reported for 138 samples from U.S. deposits (Pillay et al. 1969).

Plants. Several species of grasses and herbaceous plants accumulate selenium, and some of these are endemic to the western United States. Primary accumulators are *Astragalus*, *Oonopsis*, *Stanelya*, *Xylorhiza*, and *Machaeranthera*. Secondary accumulators are *Astor*, *Gatierreaia*, *Atriplex*, *Grindelia*, *Castillaja*, and *Comandra*. Primary accumulators can contain 100–100,000 mg/kg of plant tissue, whereas secondary accumulators contain 25–100 mg/kg of plant tissue (dry weight). Nonaccumulator plants generally contain less than 25 mg of selenium/kg of plant tissue (dry weight) (Rosenfeld and Beath 1964). In some plants, including the leaves of beets and cabbage, and in garlic, as much as 40–50% of the selenium may be in the form of selenate (Cappon 1981).

A study by Arthur et al. (1992) showed an increased uptake of selenium by terrestrial plants growing on soil-capped fly ash landfill sites. The selenium concentrations rarely exceeded 5 mg/kg, and there were no signs of selenium toxicity to plants. A similar study by Shane et al. (1988) on greenhouse vegetables

established that the uptake of selenium by these vegetables is proportional to the percentage of selenium in the growth medium. Another greenhouse study showed that four floating aquatic plants, *Azolla caroliniana*, *Eichjornia crassipes*, *Salvinia rotundifolia*, and *Lemna minor*, absorbed selenium quickly upon exposure (Horne 1991).

Animals. Aquatic animals accumulate selenium from lakes and rivers high in selenium content. Fish in the Kesterson National Wildlife Refuge in California had selenium concentrations up to 96 mg/kg, and aquatic birds had levels up to 130 mg/kg (Barceloux 1999). Selenium was detected in fish from three sites of the Pigeon River and Pigeon Lake in Michigan (Besser et al. 1996). It was determined that selenium concentrations in fish at sites receiving seepage and effluents from a coal fly ash disposal facility were considerably higher than for fish upstream from the facility. Mean concentrations of selenium in white sucker and northern pike ranged from 0.46 to 0.88 µg/g in a noncontaminated portion of the river, while concentrations in a contaminated portion of the river and lake were 1.1–2.4 µg/g (Besser et al. 1996). The mean concentrations of selenium in the feathers of five species of birds at Clear Lake, California were 3.20 µg/g (osprey), 1.38 µg/g (western grebe), 2.51 µg/g (great blue heron), 0.94 µg/g (turkey vulture), and 1.05 µg/g (mallard) (Cahill et al. 1998). The ospreys, which consume large mature fish had the highest selenium levels, while turkey vultures which rarely interact with the contaminated aquatic system and mallards which are semi-domesticated had the lowest levels. Selenium was detected in 24 of 24 black-crowned night herons from the Delaware Bay at concentrations of 2.84–5.95 µg/g (Rattner et al. 2000). The greatest levels were observed in the herons from Pea Patch Island, an island adjacent to a shipping channel for the petrochemical industry. Selenium was detected in the liver of 70 out of 70 redheads (*Athya americana*) in Louisiana and Texas at concentrations of 1.56–5.86 µg/g (Michot et al. 1994). The selenium concentration in moose liver from 12 areas of Sweden ranged from 0.0027 to 3.054 µg/g (Galgan and Frank 1995). The highest levels were observed in areas with a high degree of selenium deposition from industrial sources.

Food. In a review of the foods that contribute the highest proportion of the daily selenium intake of human populations in the United States, Schubert et al. (1987) estimated selenium concentrations in over 100 food items on the basis of 65 articles published after 1960. Table 6-3 presents the selenium concentrations for some of the food items analyzed. The quality of the data was evaluated on the basis of sample size, analytic method, sample handling, sampling plan, and analytic quality control. Schubert et al. (1987) chose not to present standard deviations or standard errors of the samples because of the different sampling biases present in the studies.

Table 6-3. Selenium Concentrations in Foods in the United States[a] (mg selenium/kg, wet weight)

Food item	Average	Minimum	Maximum	Number of acceptable samples
Fruits and vegetables				
Apples, raw	0.004	0.003	0.006	5
Carrots, raw	0.017	0.006	0.029	5
Oranges	0.015	0.013	0.018	3
Potatoes	0.013	0.004	0.023	7
Grains, nuts, and cereals				
Bread, white	0.32	0.23	0.54	6
Bread, whole wheat	0.44	0.28	0.67	3
Corn flakes	0.063	0.026	0.12	4
Special K	0.063	0.35	0.94	4
Egg noodles, dry	0.66	0.43	1.35	7
Egg noodles, cooked	0.19	0.14	0.42	2
Nuts, Brazil[b]	14.7	0.20	253	72
Dairy products				
Whole mile	0.016	0.011	0.025	4
Swiss cheese	0.083	0.062	0.10	2
Cottage cheese	0.060	0.052	0.068	2
Meat				
Chicken, cooked	0.21	0.17	0.26	2
Beef, cooked	0.26	0.15	0.52	3
Pork/ham, fresh/cured	0.33	0.19	0.51	6
Salami	0.20	0.13	0.33	2
Seafood[c]				
Salmon, canned	0.75	0.31	1.49	3
Shrimp, canned/cooked	0.64	0.21	1.61	4
Swordfish	2.84	2.54	3.44	4
Organ meats				
Beef liver, cooked	0.56	0.43	0.71	2
Beef kidney, raw	1.70	1.45	2.32	4

[a]Food is the normal source of selenium which is essential for human health. Concentrations from Schubert et al. (1987) except where noted.
[b]Secor and Lisk (1989)
[c]Bioavailability of selenium from some fish may be lower than from other foods.

In general, fruits and vegetables were found to contain less than 0.01 mg/kg, whereas root vegetables contained higher concentrations of selenium (Table 6-3). Beale et al. (1990) found milk and meat to have the same range of selenium concentrations as Schubert et al. (1987). In another study, no apparent correlation existed between the selenium concentration of canned versus fresh fruits and vegetables (Morris and Levander 1970).

Grain products varied greatly in their selenium concentration. Wheat bread and flour were high in selenium, whereas white bread and white flour contained considerably less selenium. Very low levels of selenium were found in certain processed cereals, such as corn flakes, but not in others, such as oat cereal (Morris and Levander 1970; Schubert et al. 1987).

Dairy products contained variable concentrations of selenium as well but in general contained lower levels than did meat products. Organ meats (e.g., liver and kidney) and seafoods contained higher levels of selenium than poultry or beef (Morris and Levander 1970; Schubert et al. 1987). The U.S. Fish and Wildlife Service collected 315 whole fish samples from 109 stations nationwide and analyzed them for selenium. The resulting selenium concentrations were as follows (wet weight): geometric mean of 0.42 µg/g, maximum 2.3 µg/g, and 85th percentile concentration of 0.73 µg/g (Schmitt and Brumbagh 1990). Consumption of the foods with higher selenium levels contributes to the daily intake of adequate amounts of selenium.

Analysis of commercial baby foods indicated that processing may reduce selenium levels of the food (Morris and Levander 1970).

A recent survey conducted by the U.S. Food and Drug Administration (FDA) which analyzed foods consumed in the United States during the period of 1991–1999, detected selenium in 3,654 out of 6,671 food samples analyzed (FDA 2000). The results of this survey are summarized in Table 6-4.

6.5 GENERAL POPULATION AND OCCUPATIONAL EXPOSURE

Because selenium is ubiquitous in the environment and has been detected in so many media, exposure of the general population to selenium can occur in a variety of ways, including occupational exposure, inhalation, and ingestion of selenium via drinking water, foods, and selenium supplements. For exposure via the food pathway, Schubert et al. (1987) estimated that beef, white bread, pork or ham, chicken, and eggs provide over 50% of the daily selenium intake in the U.S. population. The FDA (1982a) estimated

Table 6-4. U.S. Food and Drug Administration—Total Diet Study (TDS)—Market Baskets 91-3 through 99-1

		Selenium—summary of results							
TDS food description	TDS food number	Number of results	Number of not detected	Number of traces	Mean (mg/kg)	Standard deviation (mg/kg)	Minimum (mg/kg)	Maximum (mg/kg)	Median (mg/kg)
	Overall:	6,671	3,025	1,206	0.07	0.12	0	1.8	0.017
Whole milk, fluid	1	25	5	18	0.019	0.012	0	0.044	0.02
Lowfat (2% fat) milk, fluid	2	25	6	14	0.022	0.015	0	0.056	0.025
Chocolate milk, fluid	3	25	5	15	0.021	0.014	0	0.054	0.023
Skim milk, fluid	4	25	5	14	0.024	0.016	0	0.058	0.025
Plain yogurt, lowfat	6	25	5	9	0.031	0.019	0	0.068	0.033
Chocolate milk shake, fast-food	7	25	5	17	0.023	0.014	0	0.051	0.026
Evaporated milk, canned	8	25	4	4	0.043	0.024	0	0.102	0.047
American, processed cheese	10	25	0	3	0.183	0.025	0.097	0.231	0.178
Cottage cheese, 4% milkfat	11	25	2	4	0.083	0.039	0	0.178	0.08
Cheddar cheese	12	25	0	4	0.198	0.045	0.1	0.318	0.194
Ground beef, pan-cooked	13	25	0	1	0.197	0.052	0.127	0.333	0.187
Beef chuck roast, baked	14	25	0	0	0.251	0.058	0.15	0.379	0.24
Beef steak, loin, pan-cooked	16	25	0	1	0.256	0.063	0.13	0.439	0.24
Ham, baked	17	25	0	1	0.29	0.077	0.12	0.42	0.278
Pork chop, pan-cooked	18	25	0	0	0.46	0.16	0.245	0.808	0.448
Pork sausage, pan-cooked	19	25	0	4	0.215	0.094	0.066	0.556	0.207
Pork bacon, pan-cooked	20	25	0	0	0.38	0.15	0.186	0.836	0.323
Pork roast, baked	21	25	0	1	0.34	0.11	0.13	0.692	0.333
Lamb chop, pan-cooked	22	25	0	2	0.25	0.13	0.095	0.74	0.22
Chicken, fried (breast, leg, and thigh) homemade	24	25	0	2	0.25	0.1	0.067	0.465	0.243
Turkey breast, roasted	26	25	0	0	0.34	0.14	0.095	0.583	0.329
Liver, beef, fried	27	25	0	0	0.65	0.25	0.089	1.22	0.67
Frankfurters, beef, boiled	28	25	2	3	0.098	0.037	0	0.155	0.102
Bologna, sliced	29	25	0	5	0.134	0.037	0.07	0.239	0.13

Table 6-4. U.S. Food and Drug Administration—Total Diet Study (TDS)—Market Baskets 91-3 through 99-1 (*continued)*

TDS food description	TDS food number	Selenium—summary of results							
		Number of results	Number of not detected	Number of traces	Mean (mg/kg)	Standard deviation (mg/kg)	Minimum (mg/kg)	Maximum (mg/kg)	Median (mg/kg)
Salami, sliced	30	25	0	3	0.202	0.046	0.079	0.313	0.197
Tuna, canned in oil	32	26	0	0	0.69	0.13	0.498	1.013	0.655
Fish sticks, frozen, heated	34	26	0	1	0.168	0.035	0.076	0.257	0.171
Eggs, scrambled	35	26	0	1	0.217	0.073	0.076	0.405	0.206
Eggs, fried	36	25	0	0	0.278	0.084	0.149	0.454	0.259
Eggs, boiled	37	25	0	2	0.27	0.1	0.023	0.477	0.274
Pinto beans, dry boiled	38	25	2	6	0.076	0.043	0	0.13	0.064
Pork and beans, canned	39	25	5	10	0.034	0.023	0	0.076	0.038
Lima beans, immature, frozen, boiled	42	25	17	8	0.005	0.009	0	0.036	0
Green peas, fresh/frozen, boiled	46	25	18	5	0.007	0.013	0	0.044	0
Peanut butter, smooth	47	25	2	8	0.086	0.068	0	0.271	0.073
Peanuts, dry roasted	48	25	5	5	0.075	0.068	0	0.272	0.063
White rice, cooked	50	25	3	4	0.057	0.035	0	0.17	0.055
Oatmeal, quick (1–3 minutes), cooked	51	25	2	4	0.058	0.034	0	0.18	0.052
Wheat cereal, farina, quick (1–3 minutes), cooked	52	25	3	3	0.076	0.047	0	0.205	0.069
Corngrits, regular, cooked	53	25	6	13	0.025	0.025	0	0.095	0.019
Corn, fresh/frozen, boiled	54	25	17	6	0.007	0.012	0	0.034	0
Cream style corn, canned	56	25	18	7	0.005	0.008	0	0.029	0
Popcorn, popped in oil	57	26	5	7	0.083	0.071	0	0.267	0.073
White bread	58	25	0	3	0.211	0.075	0.05	0.363	0.197
White roll	59	25	0	0	0.265	0.076	0.144	0.41	0.266
Cornbread, homemade	60	25	1	3	0.124	0.04	0	0.194	0.123

Table 6-4. U.S. Food and Drug Administration—Total Diet Study (TDS)—Market Baskets 91-3 through 99-1 (*continued)*

TDS food description	TDS food number	Selenium—summary of results							
		Number of results	Number of not detected	Number of traces	Mean (mg/kg)	Standard deviation (mg/kg)	Minimum (mg/kg)	Maximum (mg/kg)	Median (mg/kg)
Biscuit, from refrigerated dough, baked	61	24	0	3	0.127	0.038	0.073	0.22	0.119
Whole wheat bread	62	25	0	0	0.32	0.079	0.198	0.48	0.32
Tortilla, flour	63	25	0	1	0.227	0.099	0.032	0.469	0.229
Rye bread	64	25	0	0	0.26	0.061	0.155	0.4	0.246
Blueberry muffin, commercial	65	25	0	3	0.113	0.04	0.065	0.246	0.108
Saltine crackers	66	26	1	5	0.098	0.036	0	0.197	0.1
Corn chips	67	25	5	8	0.04	0.032	0	0.099	0.034
Pancake from mix	68	25	0	5	0.136	0.074	0.05	0.39	0.129
Egg noodles, boiled	69	25	0	1	0.218	0.082	0.052	0.373	0.232
Macaroni, boiled	70	26	0	1	0.242	0.087	0.034	0.43	0.245
Corn flakes	71	26	5	4	0.057	0.048	0	0.195	0.05
Fruit-flavored, sweetened cereal	72	25	0	5	0.075	0.026	0.031	0.14	0.079
Shredded wheat cereal	73	26	7	5	0.046	0.04	0	0.13	0.044
Raisin bran cereal	74	26	5	9	0.049	0.059	0	0.297	0.035
Crisped rice cereal	75	25	1	10	0.085	0.071	0	0.216	0.044
Granola cereal	76	26	0	2	0.144	0.053	0.066	0.244	0.14
Oat ring cereal	77	26	1	0	0.23	0.078	0	0.335	0.235
Apple, red, raw	78	26	25	1	0	0.002	0	0.011	0
Orange, raw	79	26	24	2	0.001	0.003	0	0.012	0
Banana, raw	80	26	16	8	0.009	0.014	0	0.054	0
Watermelon, raw	81	26	25	1	0	0.002	0	0.012	0
Peach, raw	83	26	25	1	0	0.002	0	0.012	0
Applesauce, bottled	84	26	26	0	0	0	0	0	0
Pear, raw	85	26	26	0	0	0	0	0	0
Strawberries, raw	86	25	23	2	0.001	0.003	0	0.012	0

Table 6-4. U.S. Food and Drug Administration—Total Diet Study (TDS)—Market Baskets 91-3 through 99-1 (*continued*)

TDS food description	TDS food number	Selenium—summary of results							
		Number of results	Number of not detected	Number of traces	Mean (mg/kg)	Standard deviation (mg/kg)	Minimum (mg/kg)	Maximum (mg/kg)	Median (mg/kg)
Fruit cocktail, canned in heavy syrup	87	26	26	0	0	0	0	0	0
Grapes, red/green, seedless, raw	88	26	26	0	0	0	0	0	0
Cantaloupe, raw	89	26	16	10	0.007	0.009	0	0.025	0
Plums, raw	91	26	25	1	0	0.002	0	0.012	0
Grapefruit, raw	92	26	24	2	0.001	0.003	0	0.011	0
Pineapple, canned in juice	93	26	25	1	0.001	0.003	0	0.017	0
Sweet cherries, raw	94	20	20	0	0	0	0	0	0
Raisins, dried	95	25	24	1	0.001	0.003	0	0.014	0
Prunes, dried	96	25	25	0	0	0	0	0	0
Avocado, raw	97	25	24	1	0.001	0.006	0	0.028	0
Orange juice, from frozen concentrate	98	25	24	2	0.001	0.003	0	0.015	0
Apple juice, bottled	99	25	24	1	0.002	0.008	0	0.04	0
Grapefruit juice, from frozen concentrate	100	26	26	0	0	0	0	0	0
Prune juice, bottled	103	26	25	1	0	0.002	0	0.011	0
Lemonade, from frozen concentrate	105	26	25	0	0.002	0.009	0	0.047	0
Spinach, fresh/frozen, boiled	107	25	18	7	0.003	0.005	0	0.015	0
Collards, fresh/frozen	108	25	17	7	0.005	0.009	0	0.041	0
Iceberg lettuce, raw	109	26	24	2	0.001	0.004	0	0.014	0
Cabbage, fresh, boiled	110	26	21	4	0.003	0.007	0	0.03	0
Coleslaw with dressing, homemade	111	26	17	8	0.011	0.016	0	0.047	0
Sauerkraut, canned	112	26	14	11	0.009	0.015	0	0.071	0
Broccoli, fresh/frozen, boiled	113	26	16	8	0.011	0.027	0	0.134	0

Table 6-4. U.S. Food and Drug Administration—Total Diet Study (TDS)—Market Baskets 91-3 through 99-1 (*continued)*

TDS food description	TDS food number	Selenium—summary of results: Number of results	Number of not detected	Number of traces	Mean (mg/kg)	Standard deviation (mg/kg)	Minimum (mg/kg)	Maximum (mg/kg)	Median (mg/kg)
Celery, raw	114	26	24	2	0.001	0.003	0	0.012	0
Asparagus, fresh/frozen, boiled	115	26	5	11	0.042	0.045	0	0.217	0.034
Cauliflower, fresh/frozen, boiled	116	26	17	7	0.009	0.022	0	0.103	0
Tomato, red, raw	117	25	22	3	0.002	0.005	0	0.019	0
Tomato sauce, plain, bottled	119	26	23	3	0.003	0.008	0	0.037	0
Green beans, fresh/frozen, boiled	121	26	23	3	0.001	0.004	0	0.013	0
Cucumber, raw	123	26	25	1	0	0.002	0	0.011	0
Summer squash, fresh/frozen, boiled	124	26	22	4	0.002	0.005	0	0.019	0
Green pepper, raw	125	26	26	0	0	0	0	0	0
Winter squash, fresh/frozen, baked, mashed	126	26	24	2	0.001	0.003	0	0.012	0
Onion, mature, raw	128	26	18	8	0.006	0.01	0	0.039	0
Radish, raw	132	26	25	1	0	0.002	0	0.011	0
French fries, frozen, heated	134	26	25	1	0.001	0.003	0	0.016	0
Mashed potatoes, from flakes	135	26	21	5	0.004	0.009	0	0.035	0
White potato, boiled without skin	136	26	25	1	0.001	0.005	0	0.028	0
White potato, baked with skin	137	26	20	6	0.004	0.007	0	0.02	0
Potato chips	138	26	13	8	0.026	0.046	0	0.217	0.006
Scalloped potatoes, homemade	139	26	14	10	0.012	0.015	0	0.048	0
Sweet potato, fresh, baked	140	26	22	3	0.004	0.009	0	0.033	0
Spaghetti with tomato sauce and meatballs, homemade	142	26	0	4	0.123	0.035	0.048	0.2	0.116

Table 6-4. U.S. Food and Drug Administration—Total Diet Study (TDS)—Market Baskets 91-3 through 99-1 (*continued)*

TDS food description	TDS food number	Selenium—summary of results							
		Number of results	Number of not detected	Number of traces	Mean (mg/kg)	Standard deviation (mg/kg)	Minimum (mg/kg)	Maximum (mg/kg)	Median (mg/kg)
Beef stew with potatoes, carrots, and onion, homemade	143	26	1	5	0.07	0.026	0	0.12	0.071
Macaroni and cheese, from box mix	146	26	0	2	0.195	0.055	0.076	0.339	0.189
Quarter-pound hamburger on bun, fast-food	147	26	0	2	0.177	0.046	0.091	0.3	0.173
Meatloaf, homemade	148	26	0	2	0.191	0.048	0.074	0.3	0.195
Spaghetti with tomato sauce, canned	149	26	0	6	0.106	0.028	0.06	0.187	0.1
Lasagna with meat, homemade	151	26	0	4	0.147	0.032	0.093	0.213	0.147
Chicken potpie, frozen, heated	152	26	3	3	0.071	0.032	0	0.127	0.076
Chicken noodle soup, canned, condensed, prepared with water	155	26	5	9	0.028	0.018	0	0.06	0.03
Tomato soup, canned, condensed, prepared with water	156	26	22	4	0.002	0.005	0	0.017	0
Vegetable beef soup, canned, condensed, prepared with water	157	26	11	15	0.01	0.01	0	0.026	0.013
White sauce, homemade	160	26	6	6	0.032	0.022	0	0.076	0.035
Dill cucumber pickles	161	26	24	2	0.001	0.004	0	0.017	0
Margarine, stick, regular (salted)	162	25	24	1	0	0.002	0	0.012	0
Butter, regular (salted)	164	26	21	5	0.003	0.007	0	0.021	0
Mayonnaise, regular, bottled	166	26	11	12	0.021	0.021	0	0.078	0.024
Half & half cream	167	26	6	18	0.019	0.013	0	0.042	0.021
Cream substitute, frozen	168	26	26	0	0	0	0	0	0

Table 6-4. U.S. Food and Drug Administration—Total Diet Study (TDS)—Market Baskets 91-3 through 99-1 (*continued)*

TDS food description	TDS food number	Selenium—summary of results							
		Number of results	Number of not detected	Number of traces	Mean (mg/kg)	Standard deviation (mg/kg)	Minimum (mg/kg)	Maximum (mg/kg)	Median (mg/kg)
White sugar, granulated	169	26	26	0	0	0	0	0	0
Pancake syrup	170	26	26	0	0	0	0	0	0
Honey	172	26	26	0	0	0	0	0	0
Tomato catsup	173	26	22	4	0.002	0.005	0	0.016	0
Chocolate pudding, from instant mix	175	26	6	15	0.027	0.024	0	0.087	0.025
Vanilla flavored light ice cream	177	24	6	10	0.026	0.016	0	0.046	0.03
Chocolate cake with chocolate icing, commercial	178	26	6	11	0.035	0.022	0	0.077	0.041
Yellow cake with white icing, prepared from cake and icing mixes	179	26	7	5	0.035	0.024	0	0.075	0.042
Sweet roll/Danish, commercial	182	26	0	5	0.128	0.04	0.043	0.22	0.123
Chocolate chip cookies, commercial	183	26	6	5	0.043	0.032	0	0.123	0.045
Sandwich cookies with creme filling, commercial	184	26	5	15	0.032	0.022	0	0.081	0.029
Apple pie, fresh/frozen, commercial	185	26	17	9	0.007	0.011	0	0.033	0
Pumpkin pie, fresh/frozen, commercial	186	26	6	11	0.033	0.021	0	0.076	0.037
Milk chocolate candy bar, plain	187	26	4	4	0.046	0.025	0	0.11	0.047
Caramel candy	188	26	10	15	0.017	0.015	0	0.05	0.022
Gelatin dessert, any flavor	190	26	25	1	0.001	0.003	0	0.017	0
Cola carbonated beverage	191	26	25	1	0.001	0.003	0	0.014	0
Fruit drink, from powder	193	26	25	0	0.001	0.006	0	0.032	0

Table 6-4. U.S. Food and Drug Administration—Total Diet Study (TDS)—Market Baskets 91-3 through 99-1 (*continued)*

TDS food description	TDS food number	Selenium—summary of results							
		Number of results	Number of not detected	Number of traces	Mean (mg/kg)	Standard deviation (mg/kg)	Minimum (mg/kg)	Maximum (mg/kg)	Median (mg/kg)
Low-calorie cola carbonated beverage	194	26	26	0	0	0	0	0	0
Coffee, decaffeinated, from instant	196	26	24	2	0.001	0.006	0	0.032	0
Tea, from tea bag	197	26	25	1	0.001	0.006	0	0.032	0
Beer	198	26	21	5	0.002	0.005	0	0.015	0
Dry table wine	199	26	24	2	0.002	0.008	0	0.04	0
Whiskey	200	26	25	1	0	0.001	0	0.007	0
Tap water	201	26	25	1	0	0	0	0.002	0
Milk-based infant formula, high iron, ready-to-feed	202	25	6	18	0.017	0.011	0	0.03	0.021
Milk-based infant formula, low iron, ready-to- feed	203	25	6	18	0.018	0.011	0	0.037	0.021
Beef, strained/junior	205	26	6	12	0.028	0.02	0	0.075	0.026
Chicken, strained/junior, with/without broth or gravy	207	25	0	1	0.129	0.024	0.063	0.181	0.134
Chicken/turkey with vegetables, high/lean meat, strained/junior	208	2	0	2	0.064	0.004	0.061	0.066	0.064
Beef with vegetables, high/lean meat, strained/junior	209	2	2	0	0	0	0	0	0
Ham with vegetables, high/lean meat, strained/junior	210	2	0	2	0.102	0.033	0.079	0.125	0.102
Vegetables and beef, strained/junior	211	25	14	11	0.007	0.009	0	0.033	0
Vegetables and chicken, strained/junior	212	26	7	19	0.015	0.015	0	0.073	0.012
Vegetables and ham, strained/junior	213	26	7	18	0.016	0.012	0	0.041	0.018

Table 6-4. U.S. Food and Drug Administration—Total Diet Study (TDS)—Market Baskets 91-3 through 99-1 (*continued)*

TDS food description	TDS food number	Selenium—summary of results							
		Number of results	Number of not detected	Number of traces	Mean (mg/kg)	Standard deviation (mg/kg)	Minimum (mg/kg)	Maximum (mg/kg)	Median (mg/kg)
Chicken noodle dinner, strained/junior	214	26	6	10	0.029	0.018	0	0.064	0.032
Macaroni, tomatoes, and beef, strained/junior	215	26	5	10	0.028	0.017	0	0.06	0.032
Turkey and rice, strained/junior	216	26	7	14	0.025	0.022	0	0.095	0.025
Carrots, strained/junior	218	26	25	1	0.001	0.005	0	0.026	0
Green beans, strained/junior	219	26	24	2	0.001	0.005	0	0.019	0
Mixed vegetables, strained/junior	220	26	17	7	0.009	0.018	0	0.081	0
Sweet potatoes, strained/junior	221	26	26	0	0	0	0	0	0
Creamed corn, strained/junior	222	26	11	9	0.017	0.021	0	0.074	0.012
Peas, strained/junior	223	26	23	3	0.001	0.004	0	0.016	0
Creamed spinach, strained/junior	224	25	6	13	0.022	0.017	0	0.068	0.026
Applesauce, strained/junior	225	26	24	2	0.001	0.003	0	0.012	0
Peaches, strained/junior	226	26	26	0	0	0	0	0	0
Pears, strained/junior	227	25	24	1	0	0.002	0	0.012	0
Apple juice, strained	230	25	25	0	0	0	0	0	0
Orange juice, strained	231	26	26	0	0	0	0	0	0
Custard pudding, strained/junior	232	26	5	10	0.032	0.019	0	0.071	0.035
Fruit dessert/pudding, strained/junior	233	26	25	1	0	0.002	0	0.011	0
Fruit-flavored yogurt, lowfat (fruit mixed in)	235	26	7	14	0.022	0.015	0	0.047	0.024
Swiss cheese	236	26	0	5	0.18	0.054	0.109	0.368	0.174

Table 6-4. U.S. Food and Drug Administration—Total Diet Study (TDS)—Market Baskets 91-3 through 99-1 (*continued)*

TDS food description	TDS food number	Selenium—summary of results: Number of results	Number of not detected	Number of traces	Mean (mg/kg)	Standard deviation (mg/kg)	Minimum (mg/kg)	Maximum (mg/kg)	Median (mg/kg)
Cream cheese	237	26	4	8	0.053	0.031	0	0.099	0.054
Veal cutlet, pan-cooked	238	26	0	1	0.165	0.045	0.098	0.354	0.162
Ham luncheon meat, sliced	239	26	0	0	0.237	0.078	0.096	0.374	0.22
Chicken breast, roasted	240	25	0	1	0.27	0.12	0.09	0.623	0.228
Chicken nuggets, fast-food	241	25	0	1	0.2	0.1	0.052	0.595	0.177
Chicken, fried (breast, leg, and thigh), fast-food	242	25	0	1	0.218	0.065	0.131	0.353	0.21
Haddock, pan-cooked	243	19	0	0	0.397	0.076	0.256	0.503	0.4
Shrimp, boiled	244	25	0	0	0.38	0.1	0.2	0.574	0.369
Kidney beans, dry, boiled	245	26	8	12	0.02	0.017	0	0.051	0.019
Peas, mature, dry, boiled	246	26	10	4	0.05	0.09	0	0.457	0.034
Mixed nuts, no peanuts, dry roasted	247	25	1	0	0.53	0.39	0	1.8	0.44
Cracked wheat bread	248	26	0	0	0.285	0.065	0.209	0.448	0.269
Bagel, plain	249	26	0	0	0.311	0.085	0.165	0.518	0.299
English muffin, plain, toasted	250	26	0	0	0.263	0.068	0.144	0.402	0.25
Graham crackers	251	26	4	3	0.055	0.03	0	0.1	0.057
Butter-type crackers	252	26	4	2	0.061	0.031	0	0.102	0.069
Apricot, raw	253	21	19	2	0.001	0.004	0	0.015	0
Peach, canned in light/medium syrup	254	26	26	0	0	0	0	0	0
pear, canned in light syrup	255	26	26	0	0	0	0	0	0
Pineapple juice, from frozen concentrate	256	26	26	0	0	0	0	0	0
Grape juice, from frozen concentrate	257	26	26	0	0	0	0	0	0
French fries, fast-food	258	26	22	4	0.003	0.007	0	0.023	0
Carrot, fresh, boiled	259	26	22	4	0.002	0.006	0	0.027	0

Table 6-4. U.S. Food and Drug Administration—Total Diet Study (TDS)—Market Baskets 91-3 through 99-1 (*continued)*

TDS food description	TDS food number	Selenium—summary of results							
		Number of results	Number of not detected	Number of traces	Mean (mg/kg)	Standard deviation (mg/kg)	Minimum (mg/kg)	Maximum (mg/kg)	Median (mg/kg)
Tomato, stewed, canned	260	26	24	2	0.001	0.003	0	0.014	0
Tomato juice, bottled	261	26	20	6	0.004	0.007	0	0.023	0
Beets, fresh/frozen, boiled	262	25	22	3	0.002	0.006	0	0.023	0
Brussels sprouts, fresh/frozen, boiled	263	26	16	8	0.009	0.013	0	0.044	0
Mushrooms, raw	264	26	2	3	0.108	0.054	0	0.227	0.095
Eggplant, fresh, boiled	265	26	26	0	0	0	0	0	0
Turnip, fresh/frozen, boiled	266	26	23	3	0.002	0.006	0	0.025	0
Okra, fresh/frozen, boiled	267	26	22	3	0.003	0.008	0	0.03	0
Mixed vegetables, frozen, boiled	268	26	20	6	0.004	0.008	0	0.032	0
Beef stroganoff, homemade	269	26	0	0	0.191	0.043	0.121	0.311	0.183
Green peppers stuffed with beef and rice, homemade	270	26	3	4	0.065	0.029	0	0.113	0.066
Chili con carne with beans, homemade	271	26	3	6	0.052	0.025	0	0.09	0.057
Tuna noodle casserole, homemade	272	26	0	1	0.173	0.042	0.107	0.281	0.166
Salisbury steak with gravy, potatoes, and vegetable, frozen meal, heated	273	26	6	4	0.034	0.022	0	0.062	0.041
Turkey with gravy, dressing, potatoes, and vegetable, frozen meal, heated	274	26	0	5	0.093	0.025	0.051	0.17	0.091
Quarter-pound cheeseburger on bun, fast-food	275	26	0	0	0.18	0.041	0.108	0.331	0.18
Fish sandwich on bun, fast-food	276	26	0	0	0.184	0.04	0.109	0.281	0.189

Table 6-4. U.S. Food and Drug Administration—Total Diet Study (TDS)—Market Baskets 91-3 through 99-1 (*continued)*

TDS food description	TDS food number	Selenium—summary of results: Number of results	Number of not detected	Number of traces	Mean (mg/kg)	Standard deviation (mg/kg)	Minimum (mg/kg)	Maximum (mg/kg)	Median (mg/kg)
Frankfurter on bun, fast-food	277	26	0	3	0.199	0.048	0.096	0.315	0.197
Egg, cheese, and ham on English muffin, fast-food	278	26	0	0	0.263	0.079	0.095	0.451	0.256
Taco/tostada, from Mexican carry-out	279	26	2	3	0.103	0.039	0	0.161	0.104
Cheese pizza, regular crust, from pizza carry-out	280	26	0	0	0.239	0.053	0.138	0.332	0.235
Cheese and pepperoni pizza, regular crust, from pizza carry-out	281	26	0	0	0.229	0.067	0.068	0.381	0.225
beef chow mein, from Chinese carry-out	282	26	3	5	0.068	0.043	0	0.192	0.071
Bean with bacon/pork soup, canned, condensed, prepared with water	283	26	7	19	0.015	0.013	0	0.052	0.014
Mushroom soup, canned, condensed, prepared with whole milk	284	26	5	18	0.021	0.017	0	0.061	0.019
Clam chowder, New England, canned, condensed, prepared with whole milk	285	26	4	12	0.032	0.018	0	0.06	0.036
Vanilla ice cream	286	26	6	19	0.019	0.012	0	0.043	0.021
Fruit flavor sherbet	287	26	21	4	0.005	0.013	0	0.059	0
Popsicle, any flavor	288	26	25	1	0.001	0.006	0	0.03	0
Chocolate snack cake with chocolate icing	289	26	9	15	0.02	0.017	0	0.056	0.025
Cake doughnuts with icing, any flavor, from doughnut store	290	26	0	7	0.097	0.036	0.032	0.164	0.097

Table 6-4. U.S. Food and Drug Administration—Total Diet Study (TDS)—Market Baskets 91-3 through 99-1 (*continued)*

TDS food description	TDS food number	Selenium—summary of results: Number of results	Number of not detected	Number of traces	Mean (mg/kg)	Standard deviation (mg/kg)	Minimum (mg/kg)	Maximum (mg/kg)	Median (mg/kg)
Brownies, commercial	291	26	4	7	0.045	0.026	0	0.096	0.049
Sugar cookies, commercial	292	26	4	13	0.039	0.025	0	0.091	0.035
Suckers, any flavor	293	26	24	1	0.003	0.014	0	0.07	0
Pretzels, hard, salted, any shape	294	26	5	7	0.04	0.025	0	0.094	0.043
Chocolate syrup dessert topping	295	26	20	5	0.006	0.013	0	0.054	0
Jelly, any flavor	296	26	25	1	0.001	0.005	0	0.025	0
Sweet cucumber pickles	297	26	22	4	0.002	0.005	0	0.017	0
Yellow mustard	298	26	0	0	0.33	0.13	0.103	0.724	0.308
Black olives	299	26	25	0	0.001	0.007	0	0.038	0
Sour cream	300	26	4	20	0.027	0.022	0	0.1	0.022
Brown gravy, homemade	301	26	7	9	0.031	0.025	0	0.094	0.032
French salad dressing, regular	302	26	14	10	0.017	0.036	0	0.184	0
Italian salad dressing, low-calorie	303	26	24	2	0.002	0.006	0	0.023	0
Olive/safflower oil	304	26	25	1	0.001	0.003	0	0.014	0
Coffee, from ground	305	26	26	0	0	0	0	0	0
Fruit-flavored carbonated beverage	306	26	25	1	0.001	0.004	0	0.022	0
Fruit drink, canned	307	26	24	2	0.001	0.005	0	0.022	0
Martini	308	26	26	0	0	0	0	0	0
Soy-based infant formula, ready-to-feed	309	26	8	17	0.013	0.009	0	0.023	0.016
Egg yolk, strained/junior	310	12	0	0	0.293	0.026	0.253	0.33	0.292
Rice infant cereal, instant, prepared with whole milk	311	26	5	3	0.051	0.03	0	0.093	0.06

Table 6-4. U.S. Food and Drug Administration—Total Diet Study (TDS)—Market Baskets 91-3 through 99-1 (*continued)*

TDS food description	TDS food number	Selenium—summary of results: Number of results	Number of not detected	Number of traces	Mean (mg/kg)	Standard deviation (mg/kg)	Minimum (mg/kg)	Maximum (mg/kg)	Median (mg/kg)
rice cereal, strained/junior									
Bananas with tapioca, strained/junior	312	20	9	11	0.011	0.011	0	0.032	0.016
Beets, strained/junior	313	26	25	1	0	0.002	0	0.01	0
Split peas with vegetables and ham/bacon, strained/junior	314	15	15	0	0	0	0	0	0
Teething biscuits	316	26	8	18	0.015	0.011	0	0.038	0.017
Salmon, steaks or filets, fresh or frozen, baked									
Rice cereal with apple, strained/junior	317	26	0	0	0.192	0.052	0.109	0.356	0.188
Squash, strained/junior	318	6	0	0	0.285	0.052	0.205	0.341	0.29

that the greatest portion of daily selenium intake occurs from the ingestion of grains and cereals (51.8%) (FDA 1982a). Meat, fish, and poultry were estimated to contribute 36.4% and dairy products to contribute 9.7% (FDA 1982a).

Various estimates of the selenium intake for Americans have ranged from 0.071 to 0.152 mg/day (FDA 1982a; Levander 1987; Pennington et al. 1989; Schrauzer and White 1978; Schubert et al. 1987; Welsh et al. 1981). Schubert et al. (1987) estimated the intake of selenium for the U.S. population to be 0.071 mg/day. They based their estimate on their review of selenium concentrations in different types of foods and the amount of each type of food eaten. The amount of each food type eaten daily was estimated from the U.S. Department of Agriculture's 1977–1978 Nationwide Food Consumption Survey (NFCS). Welsh et al. (1981) estimated the mean daily selenium intake of a group of 22 Maryland residents to be 0.081 mg/day (the median was 0.074 mg/day). In California, the mean daily selenium intake of eight individuals was estimated to be 0.127 mg/day (Schrauzer and White 1978). The FDA (1982a) estimated the average daily selenium intake of the U.S. population to be 0.1523 mg/day (152.3 µg/day) (FDA 1982a). Pennington et al. (1989) estimated the daily dietary intake of selenium by age group and by sex between 1982 and 1986, based on the FDA's Total Diet Studies for those years, to be between 0.020 mg/day (20 µg/day) for infants and 0.120 mg/day (120 µg/day) for adult males between 25 and 30 years of age. These values are sufficient to meet the RDA for selenium of 0.055 mg/day for men and women (NAS 2000).

Both inorganic selenium and selenomethionine are also found in selenium supplements. The amounts in these supplements generally range from 10 to 25 µg/tablet (Goodman et al. 1990). A guide to vitamin and minerals recommends that not more than 200 µg selenium/day should be taken in any form (Hender 1990).

The mean whole blood selenium concentration of residents from 19 U.S. cities ranged from 0.10 to 0.34 mg/L with a mean value of 0.21 mg/L (Barceloux 1999). A synopsis of selenium concentrations in human tissues has been summarized in Table 3-6.

The National Occupation Hazard Survey (NOHS), conducted by the National Institute for Occupational Safety and Health (NIOSH), estimated that 108,682 workers in 15,127 plants were potentially exposed to selenium in the workplace in 1970 (NOHS 1976). These estimates were derived from observations of the actual use of selenium (1% of total estimate), the use of trade name products known to contain selenium (4%), and the use of generic products suspected of containing the selenium compounds (95%). The

largest numbers of exposed workers were heavy equipment mechanics, painters, mechanics in service stations, and special trade contractors.

Preliminary data from a second workplace survey, the National Occupational Exposure Survey (NOES), conducted by NIOSH from 1980 to 1983, indicated that 27,461 workers, including 9,330 women, in 904 plants were potentially exposed to selenium in the workplace in 1980 (NIOSH 1989). The majority of these workers were employed in the health services (e.g., nursing), as janitors and cleaners, as machine operators, in the metals industry, or in work involving food and kindred products. These estimates were derived from observations of the actual use of selenium (87% of the total estimate) and the use of trade name products known to contain the selenium compounds (13%).

Neither the NOHS database nor the NOES database contain information on the frequency, level, or duration of the exposure of workers to any of the chemicals listed therein. They are surveys that provide estimates of workers potentially exposed to the chemicals.

The average selenium concentration in the blood of 20 workers employed in a rubber tire repair shop located in Mexico was 148 µg/L, while the average concentration in a control group of 18 healthy volunteers was 100 µg/L (Sánchez-Ocampo et al. 1996). Selenium was measured in the blood of 222 coal miners at concentrations ranging from 34.9–99.5 µg/L (Orszczyn et al. 1996). Selenium content in the blood decreased with age and unexpectedly, smokers had slightly lower blood plasma concentrations than nonsmokers. Furthermore, the most exposed miners (miners exposed to coal dust for more than 10 years) had lower selenium plasma levels than recently hired miners. Although the precise mechanism explaining the decrease in selenium concentration with dust exposure and smoking is unknown, the authors speculated that the decreased selenium levels might reflect its use by the increased demand in antioxidant protection, involving glutathione-peroxidase. Concentrations of selenium in the plasma and urine of copper refinery workers was studied (Rajotte et al. 1996). The levels of selenium in the urine and plasma of the 20 workers ranged from 34.02–189.95 µg/L and 113.93–173.57 µg/L, respectively. The selenium levels in a control group that were not occupationally exposed was 26.71–118.39 µg/L (urine) and 119.51–187.35 µg/L (plasma).

6.6 EXPOSURES OF CHILDREN

This section focuses on exposures from conception to maturity at 18 years in humans. Differences from adults in susceptibility to hazardous substances are discussed in 3.7 Children's Susceptibility.

Children are not small adults. A child's exposure may differ from an adult's exposure in many ways. Children drink more fluids, eat more food, breathe more air per kilogram of body weight, and have a larger skin surface in proportion to their body volume. A child's diet often differs from that of adults. The developing human's source of nutrition changes with age: from placental nourishment to breast milk or formula to the diet of older children who eat more of certain types of foods than adults. A child's behavior and lifestyle also influence exposure. Children crawl on the floor, put things in their mouths, sometimes eat inappropriate things (such as dirt or paint chips), and spend more time outdoors. Children also are closer to the ground, and they do not use the judgment of adults to avoid hazards (NRC 1993).

Children are exposed to selenium by the same pathways that affect adults. The primary route of exposure for children is through the ingestion of food sources. Selenium has been identified in pasteurized milk and milk-based infant formulas in the United States at mean concentrations in the range of 0.011–0.070 mg/kg (Table 6-4). Children may also be exposed to selenium by breast feeding mothers. Selenium was identified in the postpartum breast milk of women at different lactation stages at concentrations of 6.1–53.4 µg/L (Li et al. 1999). Using these concentrations, the daily intake of selenium for fully breast fed infants was estimated to range from 5.2 to 17.9 µg/day. Others have reported the estimated daily dietary intake of selenium for infants as 20 µg/day, while the daily intake for adult males was estimated as 120 µg/day (Pennington 1989). Selenium was detected in the umbilical blood of 350 subjects in the Czech Republic at concentrations of 4.0–82.6 µg/L („erná et al. 1997). The concentration of selenium in the blood of 388 children (196 males, 192 females) ranged from 5.0 to 98.2 µg/L („erná et al. 1995). Selenium was detected in fetal tissues at a mean concentration of 2.8 µg/g (Robkin et al. 1973). The concentration of selenium in various tissues of infants has been reported by Dickson and Tomlinson (1967) and is summarized in Table 3-6. In areas containing low (0.42 mg/kg), medium (3.09 mg/kg), and high (9.54 mg/kg) seleniferous soils, the mean whole blood selenium levels of school children (7–14 years of age) were 0.13, 0.37, and 1.57 mg/L, respectively (Yang et al. 1989b). Selenium was detected in postmortem liver, lung, and spleen samples of infants in Glasgow, Scotland at mean concentrations of 2.24, 0.76, and 0.099 ppm, respectively (Raie 1996).

The tendency of young children to ingest soil, either intentionally through pica or unintentionally through hand-to-mouth activity, is well documented. This potential route of exposure is most likely in areas that naturally have a high selenium content in the soil. Since children often play in fields and soils, dermal exposure is possible and the inhalation of dust particles from soil surfaces is also possible. The soluble forms of selenium such as the inorganic alkali selenites and selenates are more likely to be bioavailable in soils than the relatively insoluble selenides. Children are not likely to be exposed to selenium from their parents' work clothes, skin, hair, tools or other objects removed from the workplace. Selenium is contained in some household products such as shampoos and preparations to treat dandruff and eczema (IARC 1975a). It is also contained in some dietary supplements (Goodman et al. 1990). Since it is unlikely that children would use these products without adult supervision, the potential for overexposure to selenium from these products is low, except for the possibility of accidental poisoning.

6.7 POPULATIONS WITH POTENTIALLY HIGH EXPOSURES

Because selenium is a naturally occurring element found in rocks, soils, plants, and animals, the general population is commonly exposed to selenium through diet and drinking water. As a result of the uneven distribution of selenium in the earth's crust, populations living in certain areas of the United States are exposed to greater than average levels of selenium. Areas of the United States with highly seleniferous soils and plants include South Dakota, Wyoming, Montana, North Dakota, Nebraska, Kansas, Colorado, Utah, Arizona, and New Mexico (Valentine et al. 1978). Hawaii also has high levels of selenium in the soil, but not in plants (Smith et al. 1936; Valentine et al. 1978). Human exposure to selenium occurs through the ingestion of food (including meat, milk, eggs, and vegetables) and drinking water from these areas (Smith et al. 1936). Selenium was found at elevated levels in fish from rivers, creeks, and lakes in California, North Carolina, Texas, and Utah (RTI 1993). Farmers and fishermen living in these regions may be at higher risk of selenium exposure than people living in urban areas because farmers tend to consume a larger proportion of locally grown foods, and fishermen tend to consume seafood, whereas people in urban areas tend to consume foods grown over a wider geographic area. In addition, people who irrigate their home gardens with groundwater containing high selenium levels may grow and consume plants that contain high levels of selenium because this element accumulates in some plants. Fishermen and hunters of waterfowl who regularly consume fish and game from waterways with elevated selenium levels may increase their selenium body burden, but no reports of selenosis attributable to this practice have appeared in the literature.

People living in the vicinity of hazardous waste sites or coal burning plants may also be exposed to high levels of selenium. Selenosis has been reported in residents of the Wudang Mountains, China where food was grown in highly seleniferous soil (Yang et al. 1989a, 1989b). Selenium blood levels of five patients with long persisting, distinct clinical signs of selenosis ranged from 1.054 to 1.854 mg/L (Yang et al. 1989b). To attain selenium blood levels of this magnitude, it was estimated that the daily intake must be at least 910 µg/day. The mean selenium concentration in hair samples obtained from residents of a highly seleniferous region of Glasgow, Scotland was 18.92 ppm (Raie 1996). By comparison, the mean levels for adults from Iran and Iceland were only 5.72 and 1.81 ppm, respectively.

6.8 ADEQUACY OF THE DATABASE

Section 104(i)(5) of CERCLA, as amended, directs the Administrator of ATSDR (in consultation with the Administrator of EPA and agencies and programs of the Public Health Service) to assess whether adequate information on the health effects of selenium is available. Where adequate information is not available, ATSDR, in conjunction with the National Toxicology Program (NTP), is required to assure the initiation of a program of research designed to determine the health effects (and techniques for developing methods to determine such health effects) of selenium.

The following categories of possible data needs have been identified by a joint team of scientists from ATSDR, NTP, and EPA. They are defined as substance-specific informational needs that if met would reduce the uncertainties of human health assessment. This definition should not be interpreted to mean that all data needs discussed in this section must be filled. In the future, the identified data needs will be evaluated and prioritized, and a substance-specific research agenda will be proposed.

6.8.1 Identification of Data Needs

Physical and Chemical Properties. The physical and chemical properties of elemental selenium and most of the common environmental forms of selenium have been characterized (Budavari et al. 1996; Lide 2000) and no further data are needed (see Chapter 4).

Production, Import/Export, Use, Release, and Disposal. Knowledge of a chemical's production volume is important because it often correlates with possible environmental contamination and human exposure. Current data regarding the import (USGS 2001), export (USGS 2001), and use (Hoffmann and King 1997) of selenium are available. No statistics regarding the U.S. production of

selenium have been reported since 1996 (USGS 2001). Current information on the U.S. production of selenium would assist in identifying potential exposures, particularly in regions of the country where environmental exposure to selenium through food and drinking water is already relatively high.

According to the Emergency Planning and Community Right-to-Know Act of 1986, 42 U.S.C. Section 11023, industries are required to submit substance release and off-site transfer information to the EPA. The Toxics Release Inventory (TRI), which contains this information for 1999, became available in May of 2001. This database will be updated yearly and should provide a list of industrial production facilities and emissions.

Environmental Fate. Information is available to permit assessment of the environmental fate and transport of selenium in air (NAS 1976a), water (Chau and Riley 1965; NAS 1980b; Ohlendorf et al. 1986a; Rudd and Turner 1983a; Saiki and Lowe 1987), and soil (Kabatas-Pendias and Pendias 1984, NAS 1976b). Selenium released to the air will be removed by wet and dry deposition. The forms of selenium expected to be found in surface water and the water contained in soils are the salts of selenic and selenious acids. Selenic acid (H_2SeO_4) is a strong acid. The soluble selenate salts of this acid are expected to occur in alkaline waters. Sodium selenate is one of the most mobile selenium compounds in the environment because of its high solubility and inability to adsorb onto soil particles (NAS 1976a). Selenious acid (H_2SeO_3) is a weak acid, and the diselenite ion predominates in waters between pH 3.5 and 9. Most selenites are less soluble in water than the corresponding selenates (NAS 1980b).

It has been suggested that a biological cycle exists for selenium (Shrift 1964), but certain components of the cycle remain uncharacterized. The biological transformation of selenide to elemental selenium has not been well described in the literature (see Maier et al. 1988). Further research on the biological selenium cycle might help to identify "hot spots" of selenium in the environment. For example, further investigation of parameters that influence the tendency of selenium to move from one medium to another (e.g., from soil to water) would improve fate and transport modeling efforts.

Bioavailability from Environmental Media. The available monitoring data indicate that selenium is present in samples of air (Dams et al. 1970; Harrison et al. 1971; John et al. 1973; Peirson et al. 1973; Pillay et al. 1971), water (Besser et al. 1996; CRWQCB 1988; Cutter 1989; Glover et al. 1979; Lakin and Davidson 1967; Lewis 1988; Maier et al. 1988; NCDNR 1986; Oster et al. 1988a; Schutz and Turekiam 1965; Smith and Westfall 1937), soil/sediment (Glover et al. 1979; Lemly 1997; Sindeeva 1964), human tissues (Li et al. 1999; Orszczyn et al. 1996; Yang et al. 1989a, 1989b), fish (Besser et al. 1996; Lowe et

al. 1985; May and McKinney 1981; Ohlendorf et al. 1986b), and food (Beale et al. 1990; FDA 2000; Schubert et al.1987). Thus, it can be concluded that selenium is bioavailable from the environmental media.

Food Chain Bioaccumulation. Selenium in food contributed to the highest proportion of the daily selenium intake for human populations in the United States. Fruits, vegetables, milk, meat, and grains contain very low levels of selenium. However, selenium is bioaccumulated by aquatic organisms (Chau and Riley 1965; Ohlendorf et al. 1986a; Rudd and Turner 1983a). Based on reported BCFs and BAFs (Lemly 1982, 1985), selenium is expected to bioaccumulate in fish. Some evidence indicates that under natural conditions selenium might also biomagnify in aquatic organisms (Lemly 1985; Maier et al. 1988; NCDNR 1986; Sandholm et al. 1973).

Exposure Levels in Environmental Media. Selenium has been detected in air (Dams et al. 1970; Harrison et al. 1971; John et al. 1973; Peirson et al. 1973; Pillay et al. 1971), water (CRWQCB 1988; Cutter 1989; Glover et al. 1979; Lakin and Davidson 1967; Lewis 1988; Maier et al. 1988; NCDNR 1986; Oster et al. 1988a; Schutz and Turekiam 1965; Smith and Westfall 1937), soil and sediment (Beath et al. 1946; Coleman and Delevaux 1957; Glooschenko and Arafat 1988; Glover et al. 1979; Lemly 1997; NAS 1976a; Rosenfeld and Beath 1964; Shamberger 1981; Sindeeva 1964), coal and oil (Hashimoto et al. 1970; Pillay et al. 1969), plants (Arthur et al. 1992; Cappon 1981; Horne 1991; Rosenfeld and Beath 1964; Shane et al. 1988), and food (Beale et al. 1990; FDA 2000; Schubert et al. 1987). Continued monitoring data of selenium levels in the environment are necessary to understand current exposure levels.

Reliable monitoring data for the levels of selenium and selenium compounds in contaminated media at hazardous waste sites are needed so that the information obtained on levels of selenium and selenium compounds in the environment can be used in combination with the known body burden of selenium and selenium compounds to assess the potential risk of adverse health effects in populations living in the vicinity of hazardous waste sites.

Exposure Levels in Humans. Selenium has been detected in the blood (Barceloux 1999; Orszczyn et al. 1996), urine (Gromadzinska et al. 1996), hair (Raie 1996; Yang et al. 1989a, 1989b), and nails (Yang et al. 1989a, 1989b) of exposed individuals. Various estimates of selenium intake for the U.S. populations have been reported (FDA 1982a; Levander 1987; Pennington et al. 1989; Schrauzer and White 1978; Schubert et al. 1987; Welsh et al. 1981). The largest numbers of exposed workers were

heavy equipment mechanics, painters, mechanics, and special trade contractors (NOHS 1976). Preliminary data from another workplace study indicate that workplace exposure decreased from 1976 to 1984 (NIOSH 1989). Continued monitoring data are necessary to understand and evaluate human exposures to selenium in both occupational and nonoccupational settings.

Exposures of Children. Data are available regarding the exposure and body burdens of children to selenium. Children, like adults, are primarily exposed to selenium through diet. In areas containing low (0.42 mg/kg), medium (3.09 mg/kg), and high (9.54 mg/kg) seleniferous soils, the mean whole blood selenium levels of school children (7–14 years of age) were 0.13, 0.37, and 1.57 mg/L, respectively (Yang et al. 1989b). Selenium was detected in postmortem liver, lung, and spleen samples of infants in Glasgow, Scotland at mean concentrations of 2.24, 0.76, and 0.099 ppm, respectively (Raie 1996). Children can be exposed to selenium from breast feeding mothers. Selenium was identified in the postpartum breast milk of women at different lactation stages at concentrations of 6.1–53.4 µg/L (Li et al. 1999). Using these concentrations, the daily intake of selenium for fully breast fed infants was estimated to range from 5.2 to 17.9 µg/day. Others have reported the estimated daily dietary intake of selenium for infants as 20 µg/day, while the daily intake for adult males was estimated as 120 µg/day (Pennington 1989). Since selenium is found in soil surfaces and children ingest soil either intentionally through pica or unintentionally through hand-to-mouth activity, pica is a unique exposure pathway for children. While selenium is found in some home products like shampoos (IARC 1975a) and dietary supplements (Goodman et al. 1990), this exposure route should be low and will not disproportionally affect children. Continued monitoring data are necessary to understand potentially dangerous routes of childhood exposure.

Child health data needs relating to susceptibility are discussed in Section 3.12.2 Identification of Data Needs: Children's Susceptibility.

Exposure Registries. No exposure registries for selenium or selenium compounds were located. This substance is not currently one of the compounds for which a subregistry has been established in the National Exposure Registry. The substance will be considered in the future when chemical selection is made for subregistries to be established. The information that is amassed in the National Exposure Registry facilitates the epidemiological research needed to assess adverse health outcomes that may be related to exposure to this substance.

The development of a registry of exposures would provide a useful reference tool in assessing exposure levels and frequencies. In addition, a registry developed on the basis of exposure sources would allow an assessment of the variations in exposure levels from one source to another and of the effect of geographical, seasonal, or regulatory actions on the level of exposure from a certain source. These assessments, in turn, would provide a better understanding of the needs for research or data acquisition based on the current exposure levels.

6.8.2 Ongoing Studies

A summary of some pertinent ongoing research related to selenium is reported. Federally sponsored research that was reported in the CRIS/USDA (1999), CRISP (1999), and the Federal Research in Progress (FEDRIP 2001) databases are shown in Table 6-5.

As part of the Third National Health and Nutrition Evaluation Survey (NHANES III), the Environmental Health Laboratory Sciences Division of the National Center for Environmental Health, Centers for Disease Control and Prevention, will be analyzing human blood samples for selenium and selenium compounds. These data will give an indication of the frequency of occurrence and background levels of these compounds in the general population.

Table 6-5. Ongoing Studies on Selenium

Investigator	Institute	Research Area	Reference
Odom, JW	Auburn University	Monitoring selenium concentration in Alabama soils	CRIS/USDA 2001
Suarez, DL; Amrhein C	University of California Riverside	Selenium and arsenic speciation and mobilization in irrigated soils and drainage waters	CRIS/USDA 2001
Doner, H; Amundson, R	University of California, Berkeley	Quantify selenium levels in the Tulare Drainage District, San Joaquin Valley, California.	CRIS/USDA 2001
Tanji, KK	University of California, Davis	Remove selenium from irrigation drainage waters in the San Joaquin Valley	CRIS/USDA 2001
Jury, WA	University of California, Riverside	Characterize the flow and volatilization of selenium from soils	CRIS/USDA 2001
Schulthess, CP	University of Connecticut	Study the parameters that affect the adsorption and desorption of SeO_3, SeO_4 in soils.	CRIS/USDA 2001
McDowell, LR; Ramos-Santana, R	University of Florida	Compare bioavailability and tolerance of two Se sources (organic and inorganic).	CRIS/USDA 2001
Gottschall, EB	National Jewish Medical and Research Center	Study selenium and lung cancer risks in asbestos workers	CRISP 2001
Miller, WP	University of Georgia	Study waste streams from the poultry production (manure/litter), pulp and paper (sludges and ashes), and electric utility (fly ash/bottom ash) industries in Georgia	CRIS/USDA 2001